

# PHENIX results on Levy analysis of Bose-Einstein correlation functions

Critical Point and Onset of Deconfinement, Wroclaw 2016

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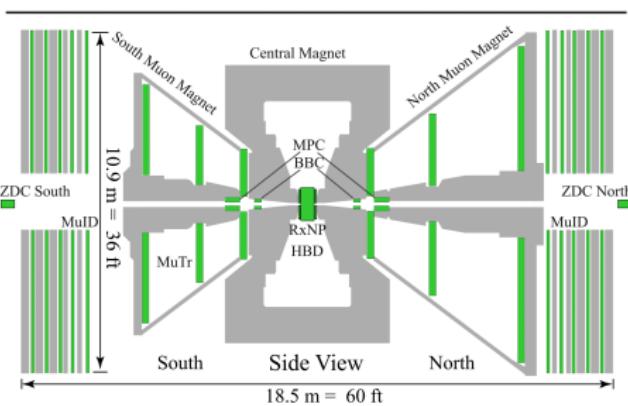
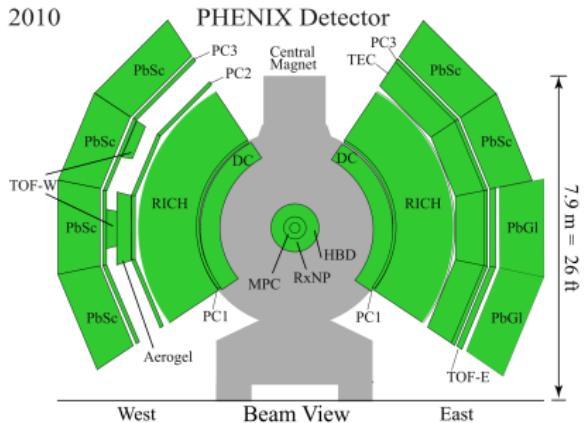


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# The PHENIX Experiment

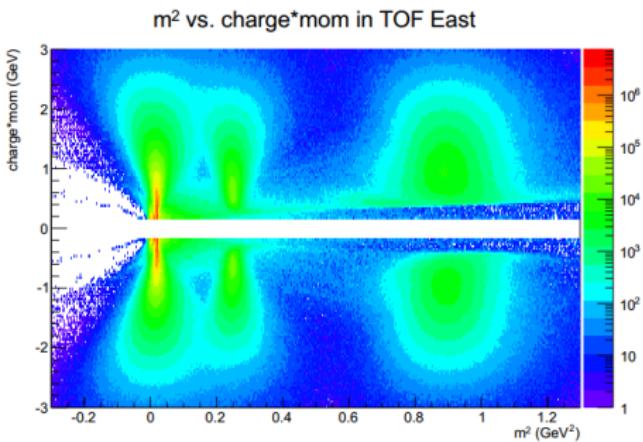
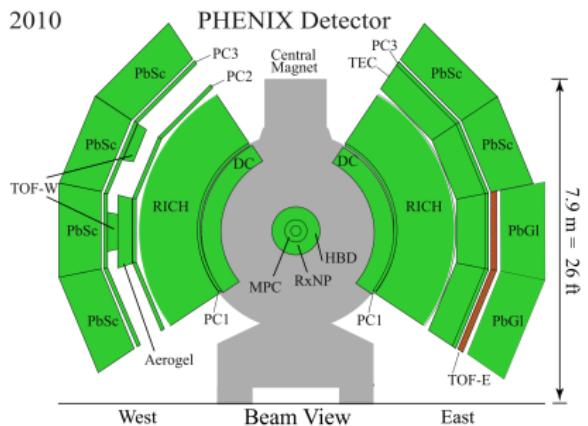
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The PHENIX detector system

- ▶ Observing collisions of p, d, Cu, Au, U
- ▶ Charged pion ID from  $\sim 0.2$  to  $2 \text{ GeV}/c^2$
- ▶ Beam energy scan is important

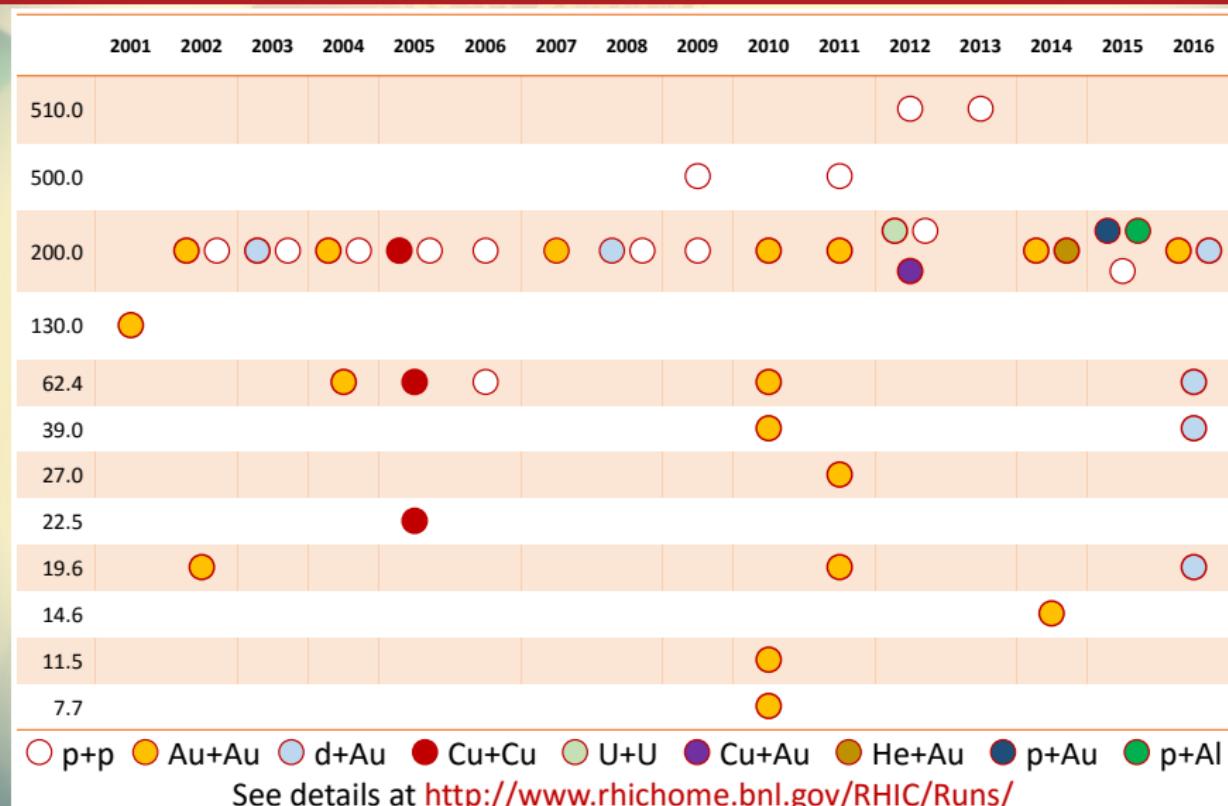
# The PHENIX Experiment



The PHENIX detector system

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# The RHIC Beam Energy Scan



# Introduction to Bose-Einstein correlations

$N_1(p), N_2(p)$  - invariant momentum distributions, the definition of the correlation function:

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_1(p_2)} \quad (1)$$

## The invariant momentum distributions

$$N_1(p) - \text{norm.}, N_2(p_1, p_2) = \int S(x_1, p_1)S(x_2, p_2)|\Psi_2(x_1, x_2)|^2 d^4x_2 d^4x_1 \quad (2)$$

- ▶  $S(x, p)$  source function (usually Gauss shaped - Lévy is more general)
- ▶  $\Psi_2$  - interaction free case -  $|\Psi_2|^2 = 1 + \cos(qx)$

If  $k_1 \simeq k_2$ :  $C_2 \rightarrow$  inverse Fourier-trf.  $\rightarrow S$

$$x = x_1 - x_2$$

$$q = k_1 - k_2$$

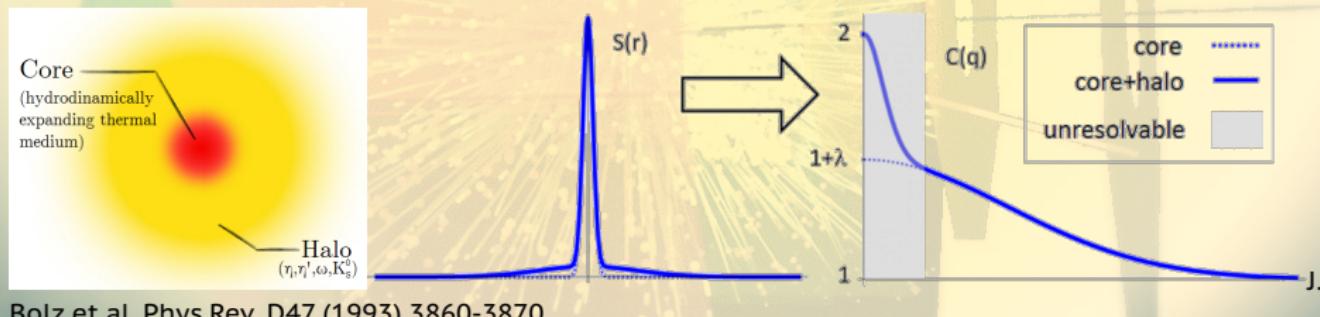
$$K = (k_1 + k_2)/2$$

$$C_2(q, K) \simeq 1 + \left| \frac{\tilde{S}(q, K)}{\tilde{S}(0, K)} \right|^2, \quad \tilde{S}(q, k) = \int S(x, k) e^{iqx} d^4x$$

- ▶ Sometimes this simple formula fails (cf. experimentally observed oscillations at L3, CMS)

# Final state interactions, resonances

- ▶ Final state interactions distort the simple Bose-Einstein picture
  - ▶ identical charged pions - Coulomb interaction
    - ▶ different methods of handling, an usual practice: Coulomb-correction
    - ▶  $C_{B-E}(q) = K(q) \cdot C_{measured}(q)$
    - ▶ An other possibility to fit with the effect incorporated in the fitted func.
- ▶ Resonance pions reduce the correlation function
- ▶  $S = S_C + S_H$
- ▶ Primordial pions - Core < 10 fm
- ▶ Resonance pions - from very far regions - Halo



Bolz et al, Phys.Rev. D47 (1993) 3860-3870

T. Csörgő, B. Lörstad and J. Zimányi, Z.Phys. C71 (1996) 491-497

# The out-side-long system, HBT radii

- ▶ Corr. func. (with Gaussian source):  $C_2(\mathbf{q}) = 1 + \lambda \cdot e^{-R_{\mu\nu}^2 q^\mu q^\nu}$
- ▶ Bertsch-Pratt pair coordinate-system
  - ▶ out direction: direction of the average transverse momentum ( $K_t$ )
  - ▶ long direction: beam direction (z axis)
  - ▶ side direction: orthogonal to the latter two
- ▶ LCMS system (Lorentz boost in the long direction)
- ▶ From the  $R_{\mu\nu}^2$  matrix,  $R_{out}, R_{side}, R_{long}$  nonzero - HBT radii
- ▶ Out-side difference -  $\Delta\tau$  emission duration
- ▶ From a simple hydro calculation:

$$R_{out}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2} + \beta_T^2 \Delta\tau^2 \quad R_{side}^2 = \frac{R^2}{1 + \frac{m_T}{T_0} \beta_T^2}$$

- ▶ RHIC: ratio is near one  $\rightarrow$  no strong 1<sup>st</sup> order phase trans.

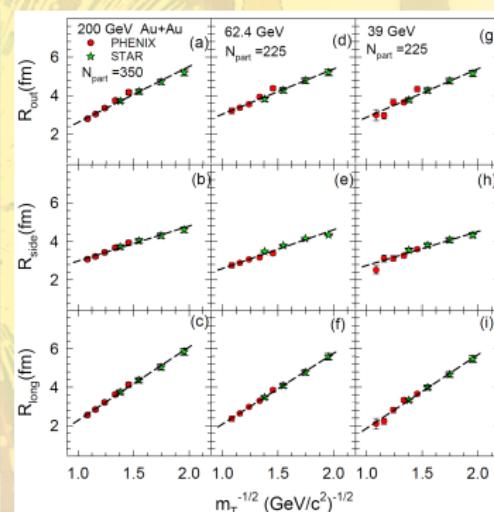
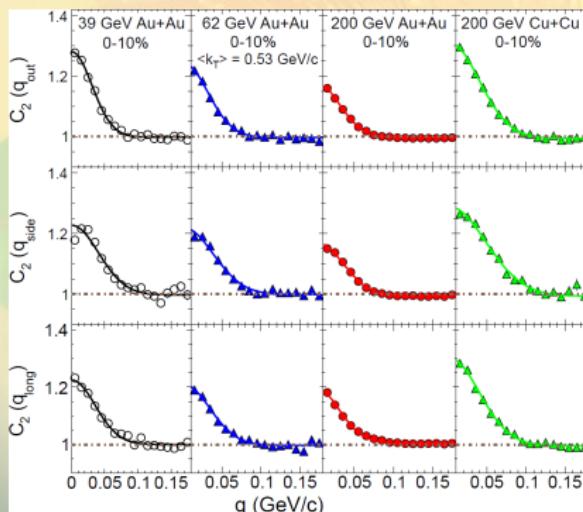
S. Chapman, P. Scotto, U. Heinz, Phys.Rev.Lett. 74 (1995) 4400-4403

T. Csörgő and B. Lörstad, Phys.Rev. C54 (1996) 1390-1403

# Beam energy & system size dependence of HBT radii

PHENIX Collaboration, arXiv:1410.2559

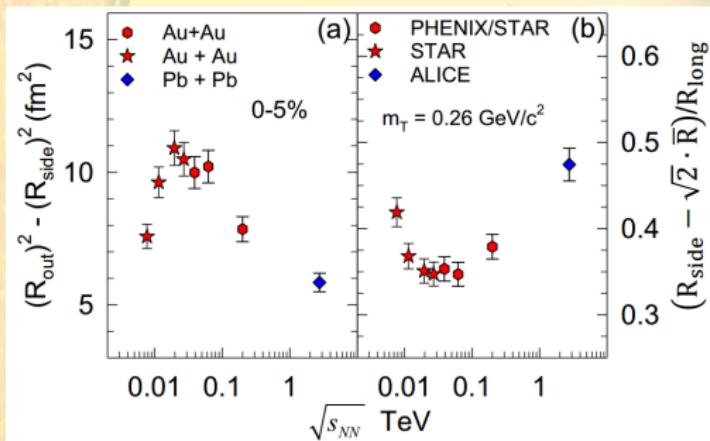
- ▶ Corr. func. in 3D, Gaussian fit (details: arXiv:1410.2559)
- ▶  $\pi^+\pi^+$ ,  $\pi^-\pi^-$  data combined
- ▶ Linear  $1/\sqrt{m_T}$  scaling of HBT radii
- ▶ Interpolation to common  $m_T$ , PHENIX and STAR consistent



# Beam energy & system size dependence of HBT radii

PHENIX Collaboration, arXiv:1410.2559

- ▶ quantities related to emission duration and expansion velocity
- ▶ non-monotonic patterns
- ▶ indication of CEP?



- ▶ More precise mapping and further detailed studies required
- ▶ Is there any other way to find the critical point?
- ▶ Maybe Levy exponent  $\alpha$ !

# A possible way of finding the critical point

## ► Generalized Gaussian - Levy-distribution

- Anomalous diffusion      }
- Generalized limit theorem      }  $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
- $\alpha = 2$  Gaussian,  $\alpha = 1$  Cauchy
- Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042
- Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) 525, nucl-th/0512060
- Csörgő, PoS HIGH-pTLHC08:027 (2008), nucl-th/0903.0669

## ► Shape of the correlation functions with Levy source:

$$C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^\alpha} \quad \begin{aligned} \alpha &= 2 : \text{Gaussian} \\ \alpha &= 1 : \text{Exponential} \end{aligned}$$

- Critical behaviour → described by critical exponents
- Spatial corr.  $\propto r^{-(d-2+\eta)}$  → defines  $\eta$  exponent
- Symmetric stable distributions (Levy) → spatial corr.  $\propto r^{-1-\alpha}$
- $\alpha$  identical to critical exponent  $\eta$

# A possible way of finding the critical point

- ▶ QCD universality class  $\leftrightarrow$  3D Ising

- ▶ Halasz et al., Phys.Rev.D58 (1998) 096007, hep-ph/9804290
- ▶ Stephanov et al., Phys.Rev.Lett.81 (1998) 4816, hep-ph/9806219

- ▶ At the critical point:

- ▶ random field 3D Ising:  $\eta = 0.50 \pm 0.05$

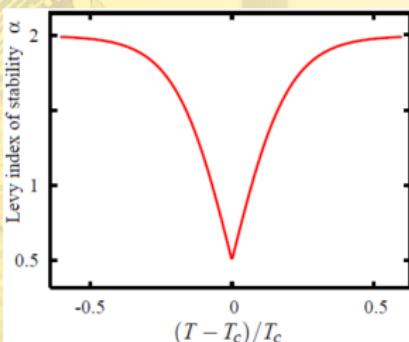
- ▶ Rieger, Phys.Rev.B52 (1995) 6659, cond-mat/9503041

- ▶ 3D Ising:  $\eta = 0.03631(3)$

- ▶ El-Showk et al., J.Stat.Phys.157 (4-5): 869, hep-th/1403.4545

- ▶ Change in  $\alpha_{\text{Levy}}$   $\leftrightarrow$  proximity of CEP

- ▶ Motivation for precise Levy HBT!



# PHENIX Levy HBT analysis & future plans

## A brief overview

### ► Dataset:

- $\sqrt{s_{NN}} = 200 \text{ GeV Au+Au, min. bias, } \sim 7 \text{ billion events} \rightarrow \text{fine } p_T \text{ binning}$

### ► Goal:

- Detailed shape analysis of 1D two-pion corr. func.
  - Levy source instead of Gaussian  $\rightarrow$  better agreement with data
- Extraction and analysis of the source parameters
  - Precision measurement of  $\lambda(m_T)$ ,  $\alpha_{\text{Levy}}(m_T)$ ,  $R_{\text{Levy}}(m_T)$
  - Lot of new physics in these results
  - Search for CEP  $\rightarrow$  lower energies

# The basics of the analysis

- ▶ Dataset used for the analysis:

- ▶ Run-10, Au+Au,  $\sqrt{s_{NN}} = 200 \text{ GeV}$ ,  $7.3 \cdot 10^9$  events

- ▶ Min. bias trigger

- ▶ Additional offline requirements:

- ▶ Collision vertex position less than  $\pm 30 \text{ cm}$

- ▶ Single track cuts:

- ▶  $2\sigma$  matching cuts in TOF & PbSc for pions

- ▶ Particle identification:

- ▶ time-of-flight data from PbSc e/w, TOF e/w, momentum, flight length
  - ▶  $2\sigma$  cuts on  $m^2$  distribution

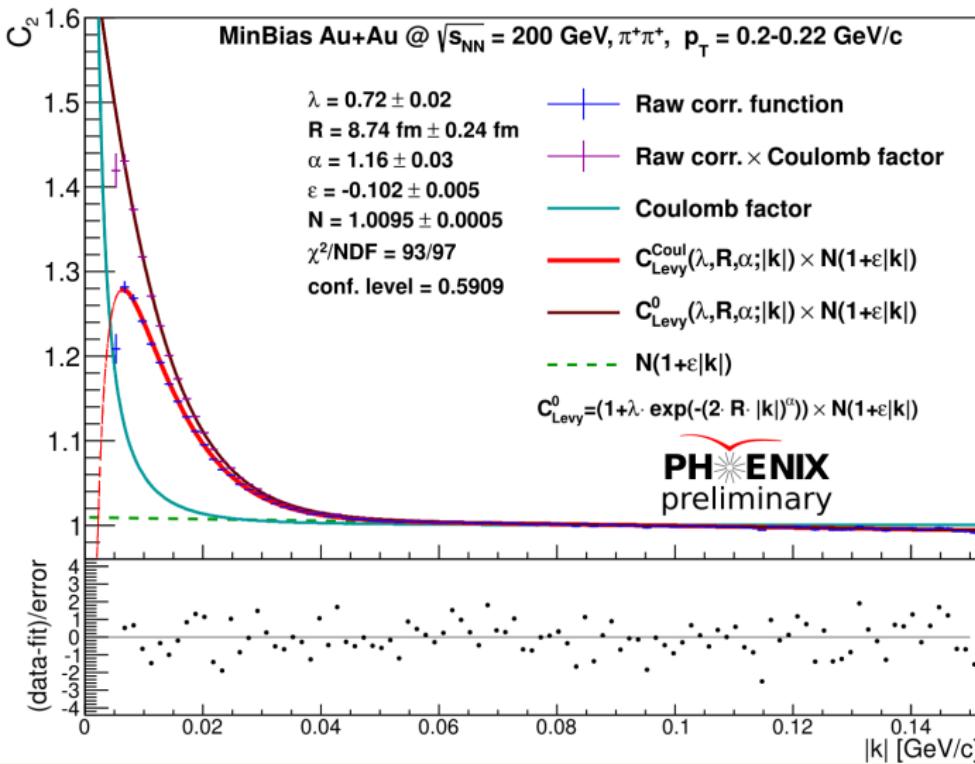
- ▶ Pair-cuts:

- ▶ A random member of pairs assoc. with hits on same tower were removed
  - ▶ customary shaped cuts on  $\Delta\varphi - \Delta z$  plane for PbSc e/w, TOF e/w

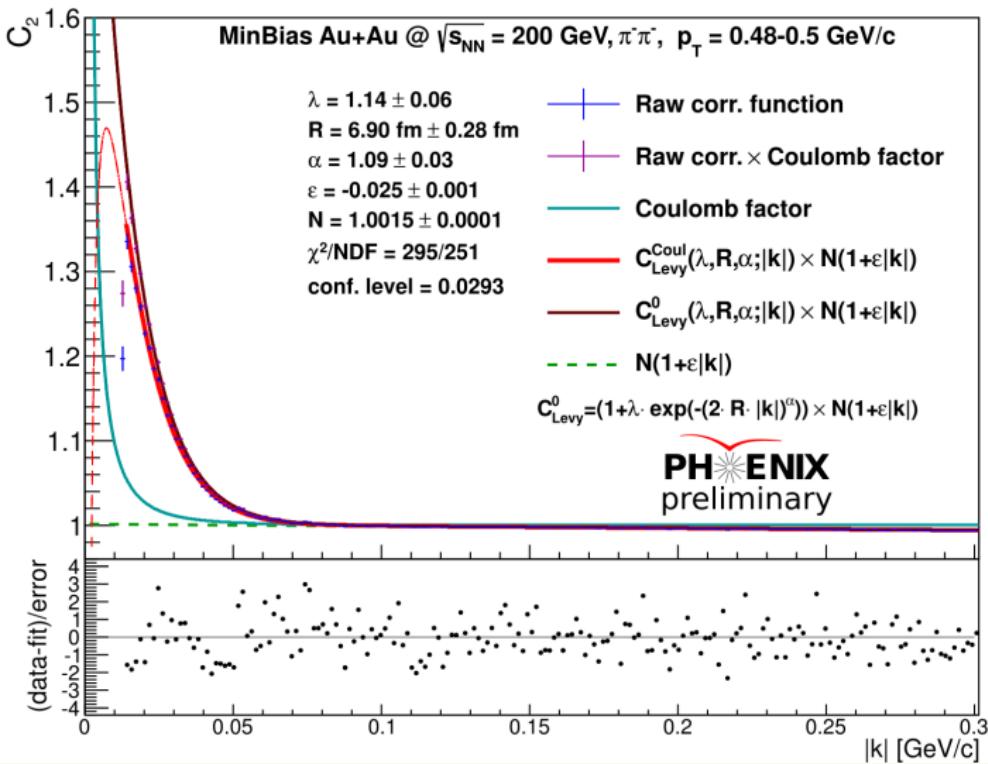
- ▶ Fit method

- ▶ Levy fits for 31  $p_T$  bins with Coulomb effect incorporated

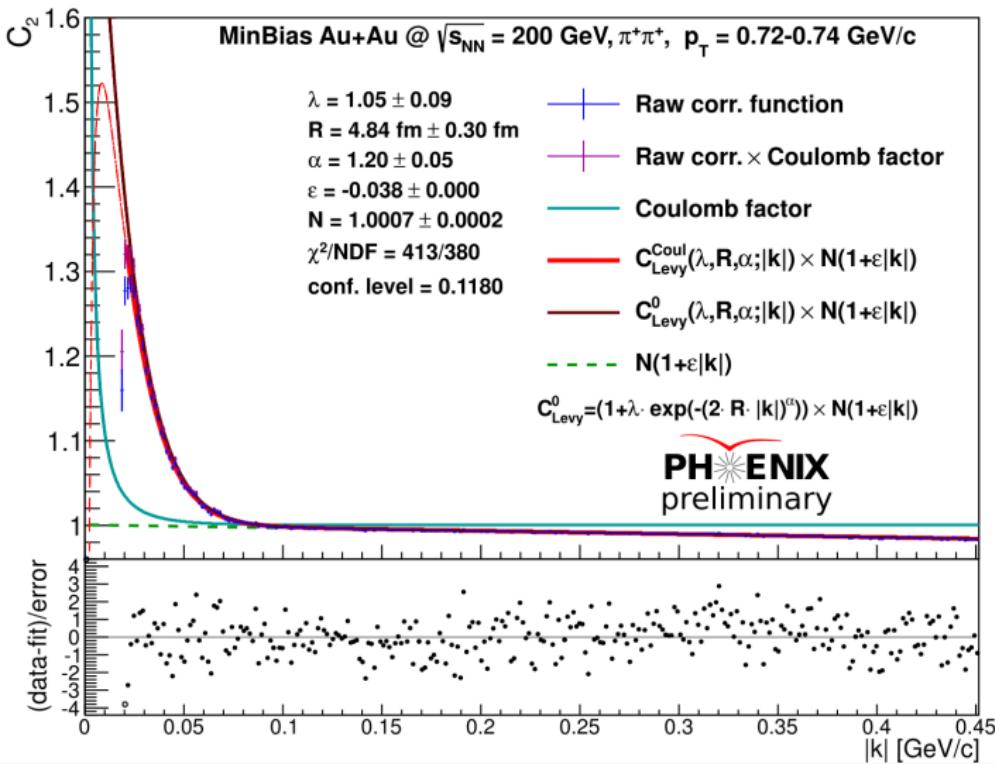
## Example correlation functions



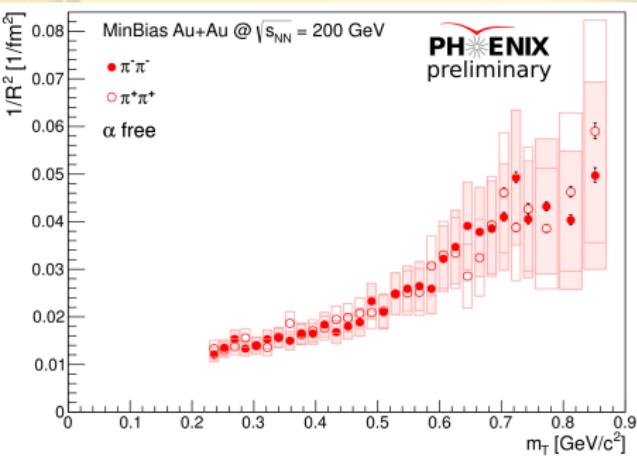
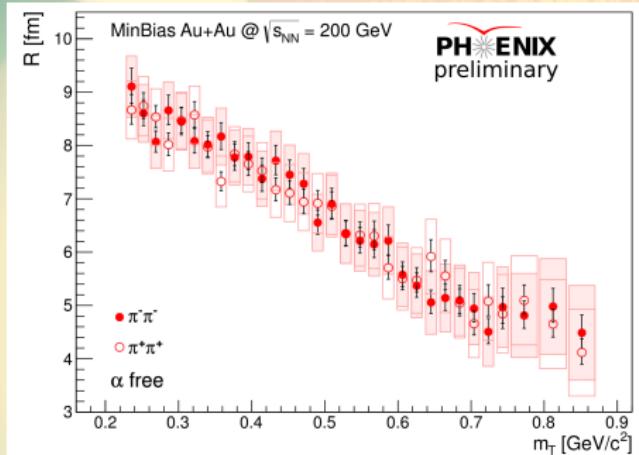
# Example correlation functions



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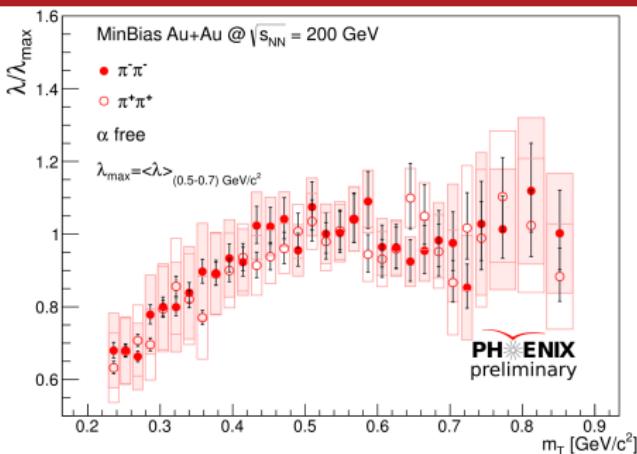
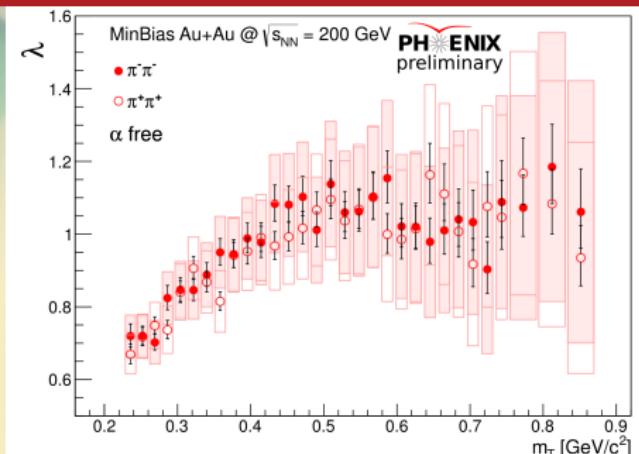


# Levy scale parameter $R$



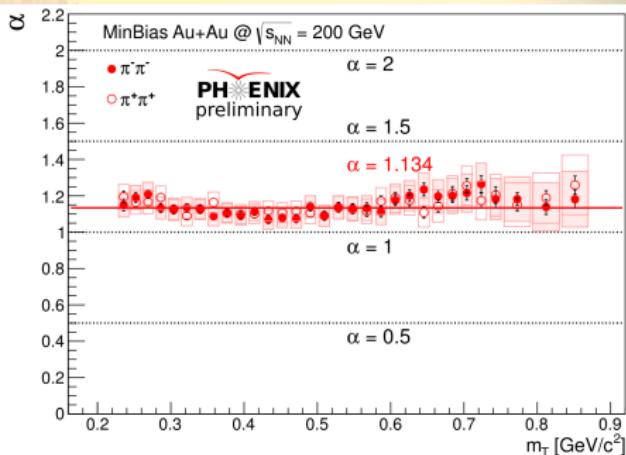
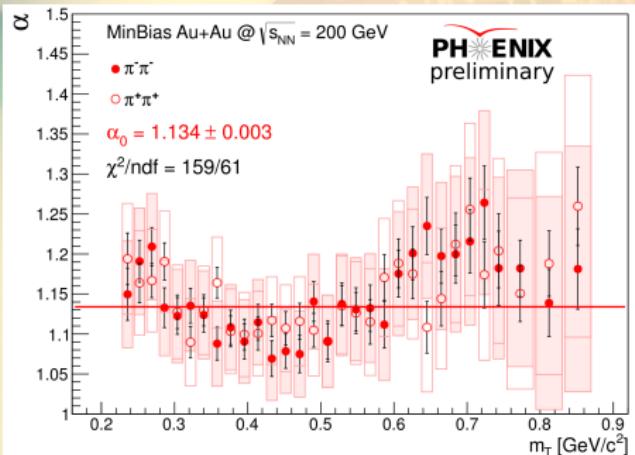
- ▶ Similar decreasing trend as HBT radii
- ▶ Hydro behaviour not invalid
- ▶ The linear scaling of  $1/R^2$  breaks for high  $m_T$

# Correlation strength $\lambda$



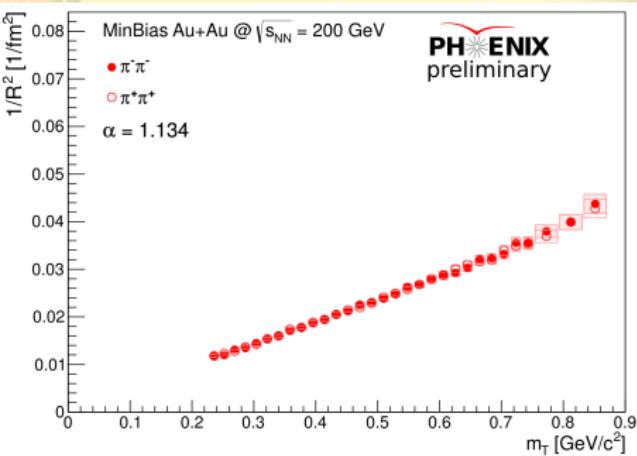
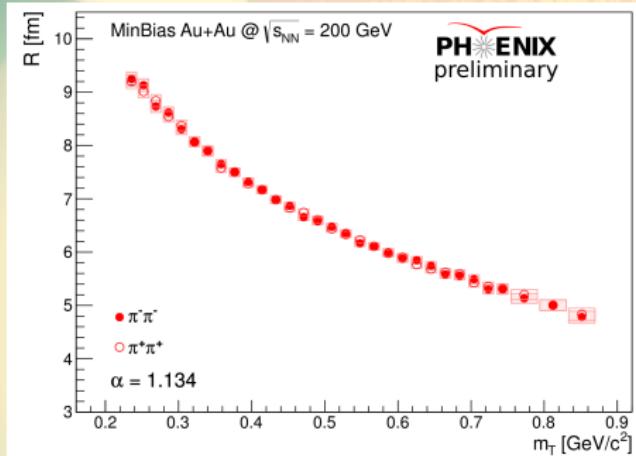
- ▶ From the Core-Halo model:  $\lambda = \left( \frac{N_c}{N_c + N_H} \right)^2$
- ▶ Observed decrease at small  $m_T \rightarrow$  increase of halo fraction
- ▶ Different effects can cause change in  $\lambda$ 
  - ▶ Resonance effects
  - ▶ Partial coherence of the fireball
- ▶ Precise measurement is important

# Levy exponent $\alpha$



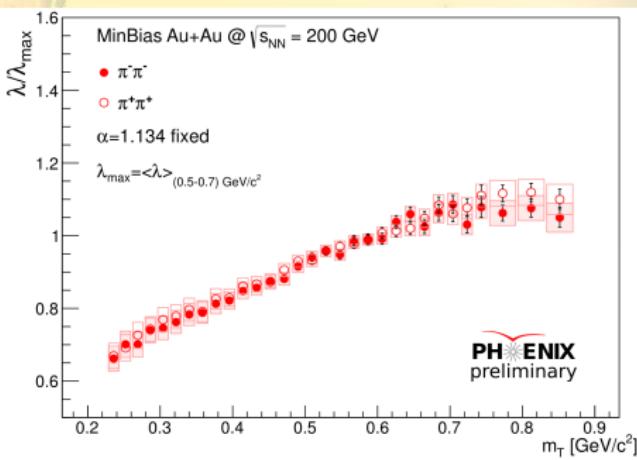
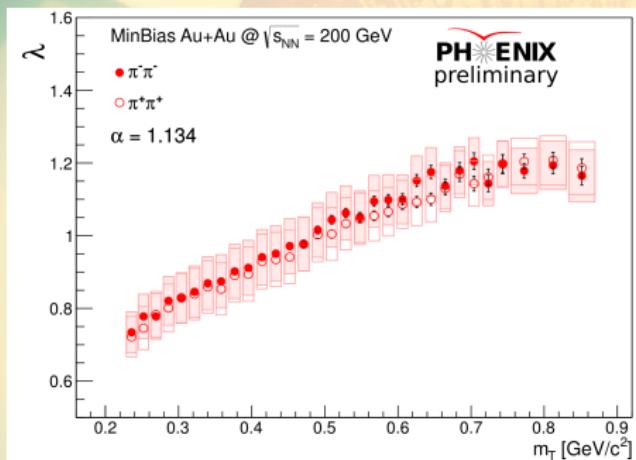
- ▶ The measured value is far from Gaussian ( $\alpha = 2$ ) and expo. ( $\alpha = 1$ )
- ▶ Also far from the rfd.3D Ising value at CEP ( $\alpha = 0.5$ )
- ▶ More or less constant (at least within systematic errors)
- ▶ Although the constant fit is statistically not acceptable
- ▶ Motivation to do fits with fixed  $\alpha = 1.134$

# Levy scale parameter $R$ with fixed $\alpha = 1.134$



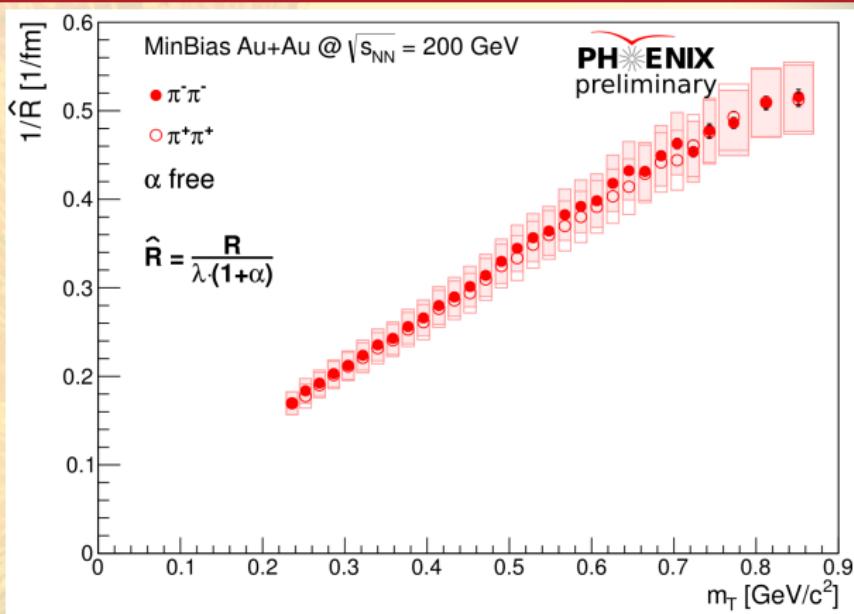
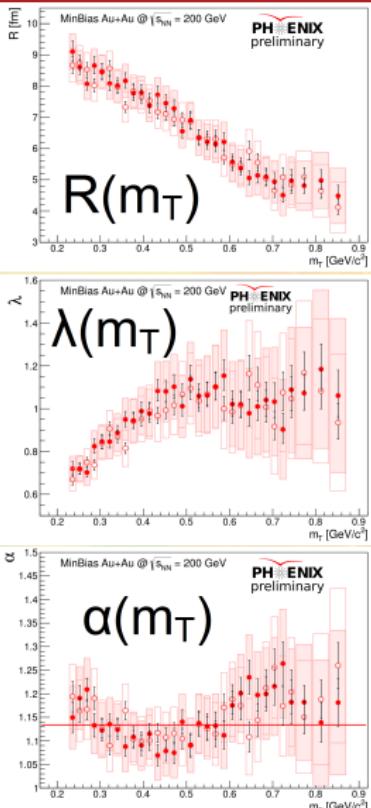
- ▶ More smooth trend
- ▶ Hydro behaviour seems to be more valid
- ▶ The linearity of  $1/R^2$  holds

# Correlation strength $\lambda$ with fixed $\alpha = 1.134$



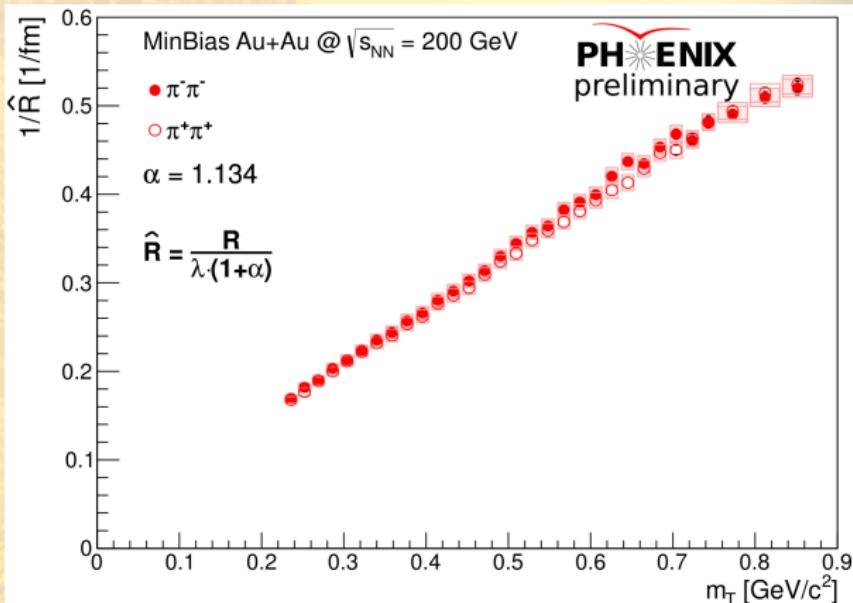
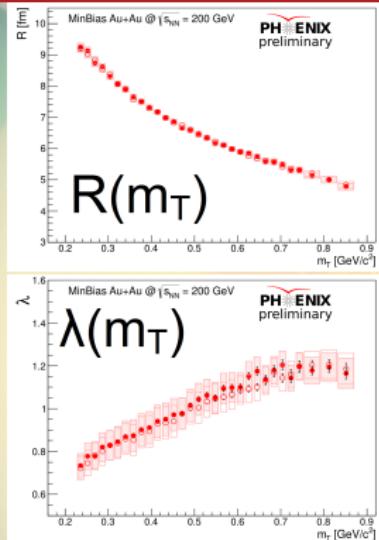
- ▶ More smooth trend
- ▶ Smaller systematic errors

# Newly discovered scaling parameter $\hat{R}$



- ▶ Empirically found scaling parameter
- ▶ Linear in  $m_T$
- ▶ Physical interpretation → open question

# Newly discovered scaling parameter $\hat{R}$



►  $\alpha = 1.134$  fixed

- Empirically found scaling parameter
- Linear in  $m_T$
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# Summary I

- ▶ Earlier PHENIX HBT result:

- ▶ Beam energy & system size dependence of HBT radii
  - ▶  $1/\sqrt{m_T}$  transverse mass scaling of HBT radii
  - ▶ Linear dependence for all systems and directions,  
PHENIX & STAR consistent
  - ▶ Specific combinations of radii vs.  $\sqrt{s_{NN}}$  show non-monotonic behaviour
  - ▶ Indication of CEP? - further detailed studies required

# Summary II

- ▶ PHENIX Levy HBT analysis preliminary results:
  - ▶ Dataset: Run-10 200 GeV Au+Au,  $\sim 7$  billion evts.
  - ▶ Precise measurement of Levy source parameters ( $R, \lambda, \alpha$ )
  - ▶ New empirically found scaling parameter  $(\hat{R})$
  - ▶ Future plans: lower energies, 3 pion corr., pion-kaon comparison
  - ▶ Expected physics info: CEP, partial coherence, resonance effects

Thank you for your attention!

I would like to invite You to the 16th Zimanyi Winter School on Heavy Ion Physics  
Budapest, Hungary, Dec. 5. - Dec. 9. 2016

<http://zimanyischool.kfki.hu/16/>